SHAKE TABLE TESTS ON PLASTERBOARD CONTINUOUS CEILINGS

G. Magliulo, V. Pentangelo, V. Capozzi, C. Petrone, G. Manfredi
University of Naples Federico II, Department of Structural Engineering, Naples, Italy

G. Maddaloni
University of Naples Parthenope, Department of Technology, Naples, Italy

P. Lopez
Etex Dry Co, Product Development Department, Avignon, France

R. Talamonti
Lafarge Gessi, Milan, Italy

ABSTRACT
In the last years, the scientific community research effort is moving towards the investigation of the seismic behaviour of nonstructural components. In this paper, full-scale experimental testing are designed and implemented to investigate the seismic behaviour of a typology of nonstructural components: the plasterboard continuous suspended ceilings. A set of five accelerograms are selected matching the target response spectrum, provided by the USA code for nonstructural components seismic qualification (AC 156). These accelerograms, representative of different intensity levels, are then applied to the test setup. Three limit states (occupancy, damage and life safety limit state) are considered in this study to characterize the seismic response of suspended ceiling systems.
The ceilings tested show no damage at all intensity level, resulting in a low fragility. An interesting comparison is made with a previous vulnerability study on a ceiling system with discrete plasterboard tiles.

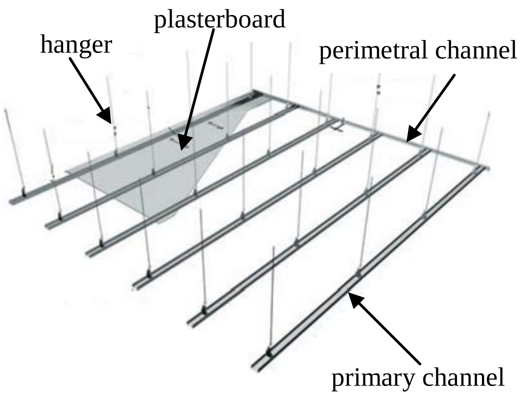
Keywords: continuous plasterboard ceiling, full scale shaking table test, seismic performance, nonstructural components.

1. INTRODUCTION

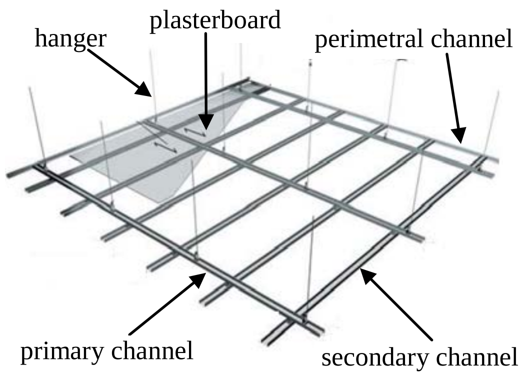
The failure of ceiling systems has been one of the most widely reported types of nonstructural damage in buildings during past earthquakes (Badillo et al. 2006, Gilani et al. 2010a). The recent L'Aquila earthquake, occurred on April the 6th, 2009, in central Italy, has widely confirmed the last assertion: the most part of the evacuated buildings showed undamaged structural elements and moderate-to-heavy damaged nonstructural components, especially ceiling systems (Magliulo et al. 2009).
The damage of the nonstructural components gives the largest contribution to the economic loss due to an earthquake. In fact, structural cost represents a small portion of the total one, corresponding to 18%, 13% and 8% for offices, hotels and hospitals respectively (Taghavi and Miranda 2003). For these reasons, the knowledge of the seismic performance of nonstructural elements is essential.
An extensive study aimed at the fragility curve evaluation of ceiling system composed of tiles supported by metallic grids was carried out in Buffalo via shake table test (Badillo-Almaraz et al. 2007, Gilani et al. 2010a).
In this paper, the seismic behaviour of plasterboard continuous suspended ceilings under strong earthquakes is investigated. The ceiling system differs from the systems of the previous studies for its "continuous" nature: it consists of a unique plasterboard panel obtained connecting few boards each other. The vulnerability evaluation of this particular plasterboard ceiling system is the main goal of the research. This aim is pursued via shake table tests: this experimental facility is particularly needed in this case since suspended ceiling systems are not amenable to traditional structural analysis.
A comparison with tests on a U.S. common ceiling system is also presented.

2. DESCRIPTION OF THE EXPERIMENTAL TESTS

Two typologies of plasterboard continuous suspended ceilings are tested: single frame ceiling (SFC) and double frame ceiling (DFC) systems. A schematic representation of the two used systems is shown in Fig. 2.1(a) and Fig. 2.1(b) respectively.



(a)



(b)

Figure 2.1. Suspended plasterboard continuous ceilings: (a) single frame ceiling (SFC); (b) double frame ceiling (DFC)

The seismic qualification of suspended ceiling is carried out by the earthquake simulator system available at the laboratory of Structural Engineering Department of University of Naples Federico II. The system consists of two 3 m x 3 m square shake tables but only is used in this experimental campaign.

With the purpose of simulating the seismic effects on the ceilings, a steel test frame is properly designed and built (Fig. 2.2). The test frame is of S275 steel material with concentric V-bracings made of steel U-section (UPN160). The very stiff test frame is required in order to control the acceleration on the specimen and to avoid shake table – test frame – ceiling system double-resonance issues.

Two U-section profiles (UPN100) are welded around the perimeter of the test frame, at a distance of 20 cm and 50 cm from the roof; a 40 mm x 100 mm timber ledger is inserted in the U-section profile in order to easily laterally restrain the ceiling system. Indeed, the ceiling system plasterboards are connected along the perimeter of the frame to the timber ledger. Consequently, the light mass and the large stiffness of the timber-channel profiles system represent the typical boundary conditions of a ceiling on structural elements. The total weight of the test frame is equal to 19.2 kN.

Figure 2.2. Test frame installed on the shake table

The tested specimen is composed by three plasterboards connected one another via stucco, both for SFC and DFC. The total dimension of the specimen is 2.20 m x 2.20 m.
Accelerometers and strain gauges are used to monitor the response of the test frame and plasterboard ceilings in both ceiling system configurations.
In order to adequately measure the seismic behaviour of the specimen, three triaxial accelerometers are installed at the centre and at the edges of the roof, as shown in Figure 2.3; one is also placed at the base of the frame, in order to verify the real input transmitted to the specimen from the shaking table.

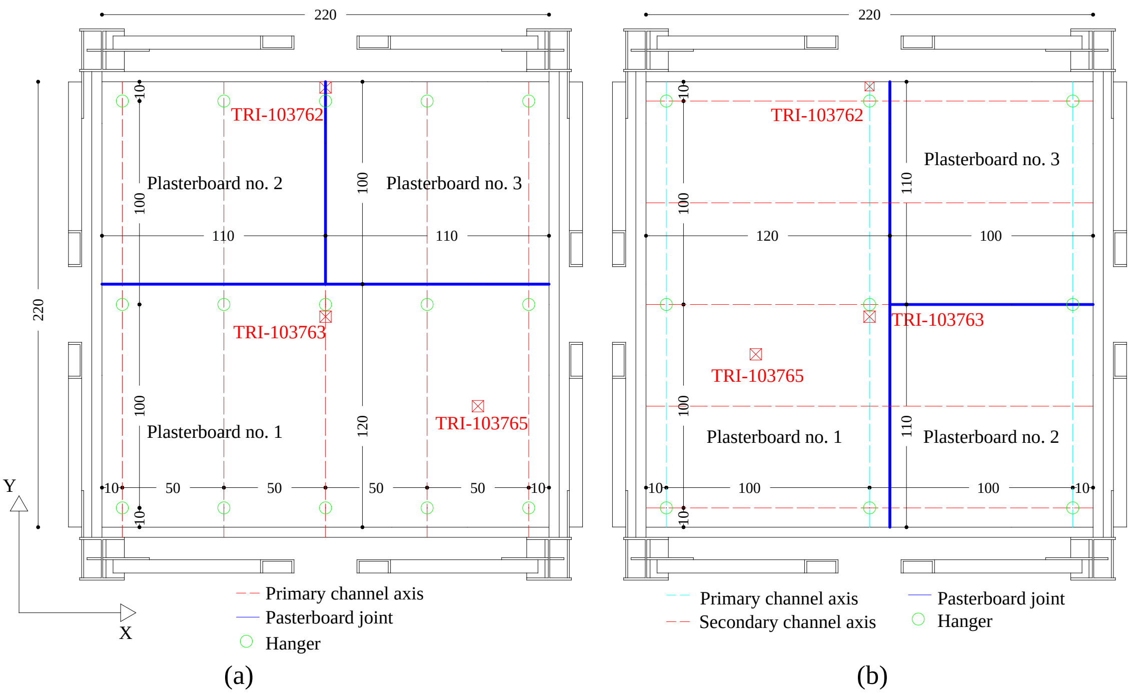
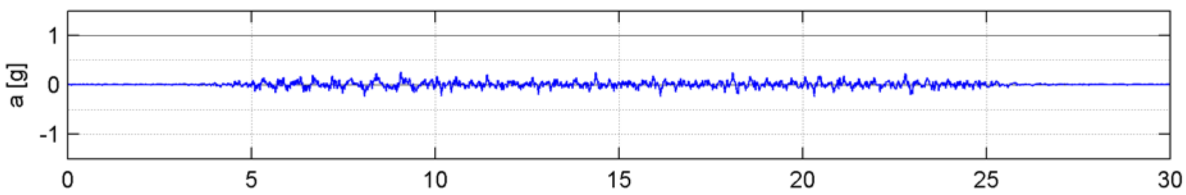


Figure 2.3. Triaxial accelerometers, plasterboard and hanger position in the case of single frame ceiling (a) and double frame ceiling (b) specimen

A set of five accelerograms, used as input for the shakings, are opportunely selected matching a target response spectrum or required response spectrum (RRS), provided by the ICBO-AC156 code "Acceptance criteria for seismic qualification testing of nonstructural components" (ICBO, 2000).
The RRS is obtained as a function of the design spectral response acceleration at short periods, S_{DS}, depending on the site soil condition and the mapped maximum earthquake spectral acceleration at short periods (for more details see section 6.5 in ICBO-AC156).
The selection procedure of the accelerograms is performed, for a RRS corresponding to S_{DS}=1.50g; the so obtained record is then scaled to match other four levels of the target spectrum (corresponding to SDS 0.30g, 0.60g, 0.90g and 1.20g). The input motion for the different intensities are presented in Fig. 2.4.
Additional information on testing specifications is present in Magliulo and Manfredi (2011).



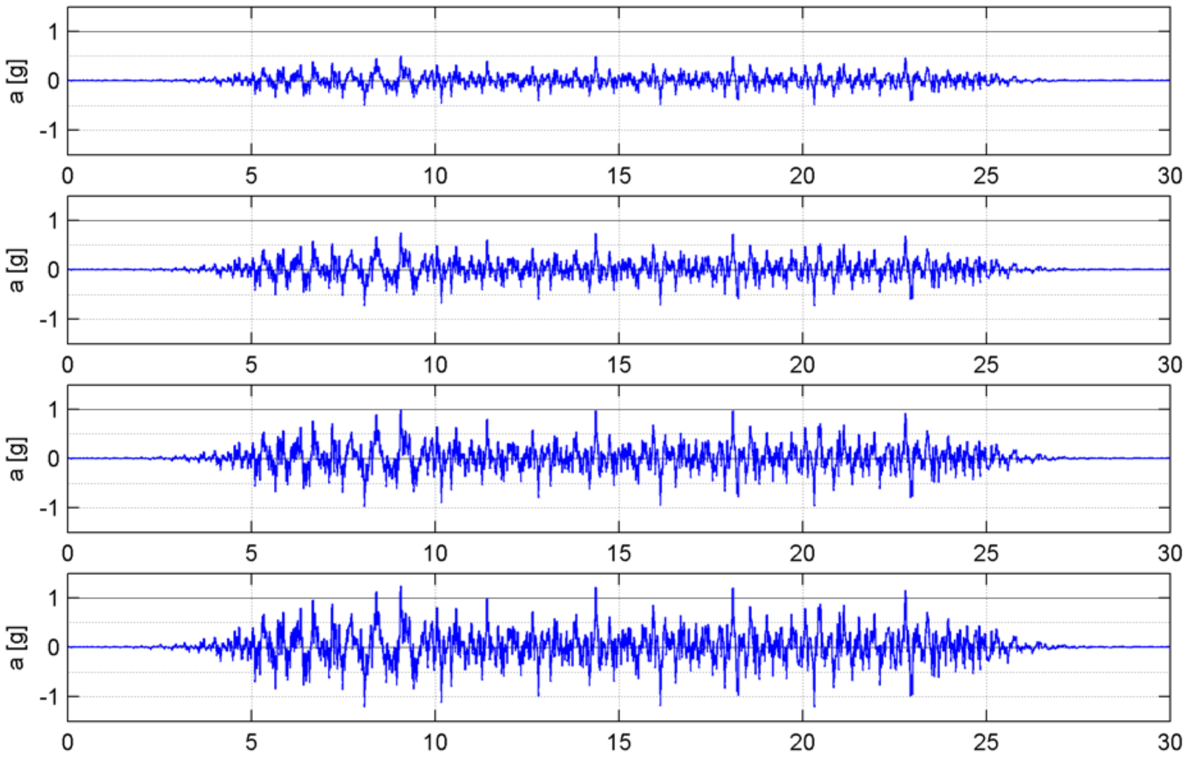
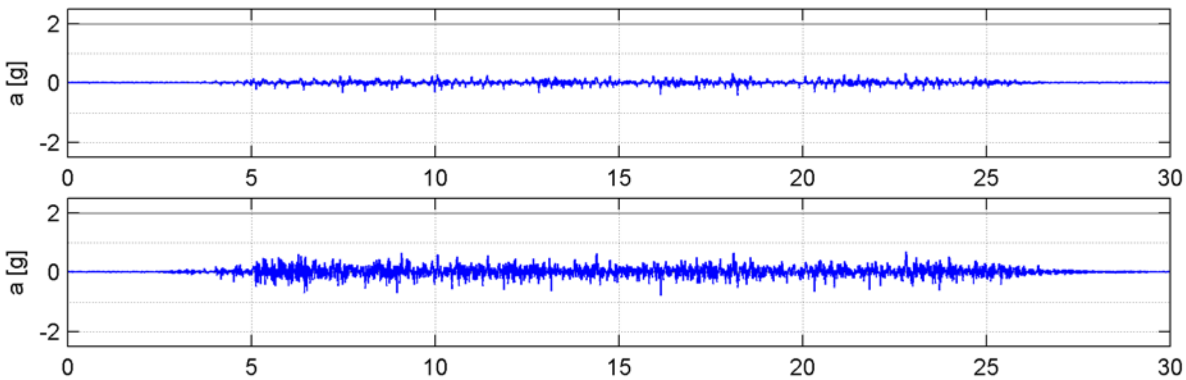


Figure 2.4. Input acceleration time histories for Y direction corresponding to SDS equal to 0.30g, 0.60g, 0.90g, 1.20g and 1.50g.

3. RESULTS

Using the selected drive motions, five unidirectional shaking tests are performed for both ceiling systems. In Figure 3.1 the acceleration time history recorded on the ceiling is presented, while in Tables 3.1 and 3.2 the maximum recorded values of acceleration on the ceilings and on the test frame roof are listed and compared to the maximum acceleration registered at the base of the shaking table. This comparison is done both for single (Table 3.1) and for double frame ceiling (Table 3.2). Values greater than 2.0g, due to dynamic amplifications in the specimen, are recorded on the ceiling. This aspect may be crucial when the build of a fragility curve is the main goal of the research. For this reason, the procedure described in Maddaloni et al. (2010), concerning the optimization of a signal recorded at desired locations, i.e. on the ceilings, will be taken into account in the next experimental campaigns.



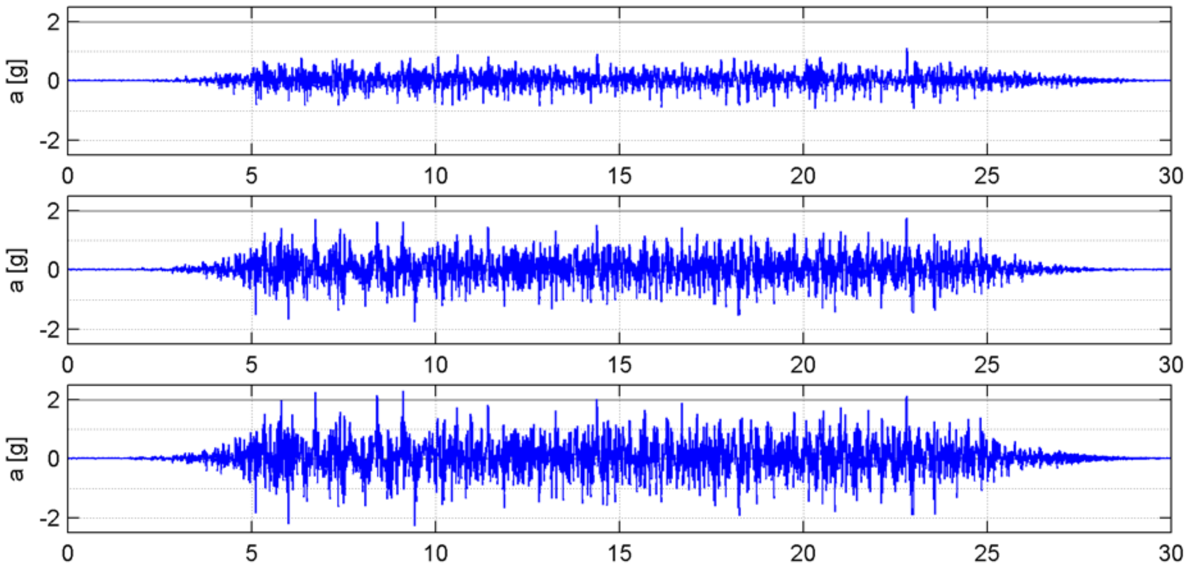


Figure 3.1. Acceleration time histories recorded on the ceiling (Accelerogram no. 103763) for single frame ceiling (SFC) for the intensity levels corresponding to SDS equal to 0.30g, 0.60g, 0.90g, 1.20g and 1.50g.

Table 3.1. Maximum recorded accelerations at base, roof and ceiling level - single frame ceiling test

Position	Ceiling	Roof	Base
test no. 1	0.42g	0.45g	0.25g
test no. 2	0.78g	0.78g	0.50g
test no. 3	1.10g	1.15g	0.69g
test no. 4	1.79g	1.90g	1.04g
test no. 5	2.28g	2.51g	1.36g

Table 3.2. Maximum recorded accelerations at base, roof and ceiling level - double frame ceiling test

Position	Ceiling	Roof	Base
test no. 1	0.42g	0.46g	0.28g
test no. 2	0.69g	0.75g	0.52g
test no. 3	1.07g	1.18g	0.75g
test no. 4	1.84g	2.06g	1.06g
test no. 5	2.36g	2.58g	1.35g

In this study, three limit states are considered in order to characterize the seismic response of suspended ceiling systems: (a) occupancy limit state (SLO); (b) damage limit state (SLD); (c) life safety limit state (SLV). The limit states are defined quantitatively by the number of damaged components (indicated as percentage of damage). From the first to the third considered limit state the damage in the ceiling increases (10%, 30% and 50% damage respectively).

After each shaking level, damage is observed inspecting physical conditions of the components. Concerning the main components of the SFC system (see Fig. 2.1(a)) indicated as primary and perimetral channels, hangers, plasterboards panels and connections, the number of damaged elements observed during the test performed with intensity level S_{DS} equal to 1.50g is indicated in Table 3.3. The table also reports for each component the total number of elements for the single frame ceiling system, the damage typology and the limit number of damaged elements required to reach a limit state. As clearly shown in the Table 3.3, no damage is recorded, though the high level of horizontal accelerations experienced. The same result is obtained for double frame ceiling system.

Table 3.3. Form for recording damage observed during the test performed on single frame ceiling with intensity level SDS equal to 1.50g

Elements	Number	Damage	SLO (10%)	SLD (30%)	SLV (50%)	Damaged elements
Hangers	15		2	5	8	0
Primary channels	5	buckling	1	2	3	0
		bending				0
Perimetral channels	4	buckling	1	1	2	0
		bending				0
Plasterboard-channel connections (screws)	87	shear	9	26	43	0
		tension				0
		punching shear				0
Plasterboards	3	collapse	-	-	1	0

An interesting comparison with a previous vulnerability study performed by Badillo-Almaraz et al. (2006) on typical U.S. ceiling system with discrete tiles is made. The tests were performed at the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University of Buffalo.
In order to make a comparison, the fragility curve for ceilings with undersized tiles (Badillo-Almaraz et al. 2007) in terms of PFA is considered (Fig. 3.1). This fragility curve, at the acceleration equal to 1.35 g, which is the maximum acceleration of the shaking table (see Tables 3.1 and 3.2) attained during the tests performed in Naples, gives 100% probability of exceeding minor and moderate damage state and 29% probability of exceeding major damage state. As already said, the ceilings tested in Naples, instead, show no damage at all intensity levels of the tests, resulting in a lower fragility with respect to the ceiling systems tested in Buffalo. Three main reasons may be the cause of this different vulnerability: (a) the continuous nature of the tested ceiling, that improves the seismic behaviour with respect to the ceilings with tiles; (b) the dense steel channel grid (the “primary channel” span is 500 mm and 1000 mm for SFC and DFC systems respectively, the “secondary channel” span is 500 mm for DFC system), that connects one another the plasterboards in a unique horizontal element, ensuring high in plane stiffness and strength; (c) the large number of hangers that connects the ceiling system to the roof, ensuring an adequate out of plane stiffness and strength, avoiding any ceiling vertical movement; (d) the smaller dimensions of the specimen tested in Naples with respect to the specimen tested in Buffalo (2.20m x 2.20m vs 4.88m x 4.88m), considering that very recent studies seem to show that specimen dimensions can affect the ceiling seismic response.

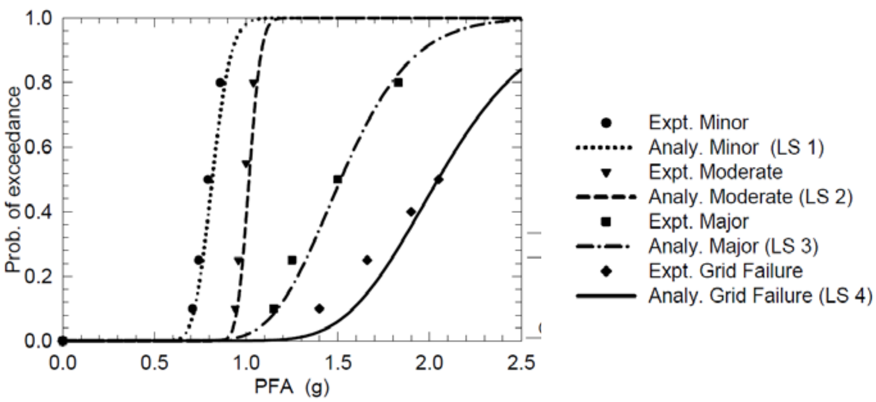


Figure 3.2. Ceiling fragility curve: ceiling with undersized tiles (Badillo-Almaraz et al. 2007)

The tests are performed shaking the table only in one direction. No vertical excitation is applied to the specimen. For the tested continuous ceiling systems, this component is not assumed as crucial. Indeed, the continuous plasterboard is connected to the roof with many vertical steel hangers (span is equal to

1 m along both the horizontal directions) with a sufficient axial stiffness (for steel hanger design, a safety factor larger than 3 is considered). Hence, no failure due to earthquake vertical component is expected.

4. CONCLUSIONS

Shaking table tests are performed to investigate the seismic behaviour of plasterboard continuous suspended ceilings under strong earthquakes. Two typologies of continuous plasterboard ceilings (i.e. single frame ceiling (CSO) and double frame ceiling (CDO)) are tested. The ceilings tested shows no damage at all intensity level (the acceleration on the ceiling ranges from 0.40g to 2.36g), resulting in a low fragility.

Three main reasons may be the cause of this low fragility: (a) the continuous nature of the tested ceilings; (b) the dense steel channel grid; (c) the large number of hangers that connects the ceiling system to the roof, avoiding any ceiling vertical movement.

Finally, an interesting comparison with a previous vulnerability study performed by Badillo-Almaraz et al. in 2007 on typical U.S. ceiling with tiles systems was performed. The comparison points out the lower fragility of continuous plasterboard ceiling systems, tested in Naples, with respect to the ceiling systems with discrete tiles, tested in the U.S.; however, this conclusion could be influenced by the smaller dimensions of the specimen tested in Naples with respect to the specimen tested in Buffalo.

AKCNOWLEDGEMENT

This research study has been funded both by Italian Department of Civil Protection in the frame of the national project DPC - ReLUIS 2010-2013 and by Lafarge that also provided the ceiling components for the testing program.

REFERENCES

Badillo-Almaraz H, Whittaker AS, Reinhorn AM, Cimellaro GP (2006) Seismic Fragility of Suspended Ceiling Systems, Report MCEER-06-0001, MCEER/SUNY/Buffalo.

Badillo-Almaraz H, Whittaker AS, Reinhorn AM (2007) Seismic fragility of suspended ceiling systems. Earthquake Spectra 23(1):21–40.

Gilani ASJ, Reinhorn AM, Glasgow B, Lavan O, and Miyamoto HK (2010a) Earthquake simulator testing and seismic evaluation of suspended ceilings. ASCE/J Archit Eng, 16(2):63-73.

International Conference of Building Officials (ICBO) (2000) ICBO AC 156 Acceptance Criteria for the Seismic Qualification of Nonstructural Components. ICBO Evaluation Service, Inc., Whittier, California, USA.

Maddaloni G, Ryu KP, Reinhorn AM (2010) Simulation of floor response spectra in shake table experiments. Earthq Eng Struct Dyn. DOI: 10.1002/eqe.1035.

Magliulo G, Manfredi G (2011) Shake table tests for analysis of the seismic performances of Lafarge pregymetal ceilings. Report 2010078-01, Department of Structural Engineering, University of Naples Federico II, Italy.

Magliulo G, Pentangelo V, Manfredi G (2009) Danneggiamento delle controsoffittature a seguito del terremoto dell’Aquila dell’aprile 2009 V1.00, available on http://www.reluis.it (in Italian).

Taghavi S, Miranda E (2003) Response assessment of nonstructural building elements, PEER report 2003/05, College of Engineering, University of California Berkeley, USA.